Counting the Cost of Machinery Health Monitoring in the Steel Industry

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Abstract: A model developed originally at Glaxo Wellcome Operations, U.K. Ltd., by B.S.Rajan has been adapted and modified in order to assess its suitability for application in the steel industry; exemplified typically by the maintenance requirements of the Hot Rolling Mill. Several models were investigated and evaluated, from which, Rajan's model was selected. The direct repair cost and consequential cost savings are established and examined in relation to the cost of carrying out machinery condition monitoring. A sensitivity test was undertaken to identify the most critical factors which control costs. These were found to be: probability of detection of machine deterioration, machine reliability, standby facility, system downtime duration, and the efficiency of condition monitoring utilisation.

Keywords: Condition monitoring, economic justification, cost benefit, maintenance, management tool

Introduction: Condition monitoring plays an increasingly important part in modern maintenance practice. However, there are some unfavourable aspects which have hindered the progress in ensuring that such methods are utilised to the very best advantage and are, therefore, fully cost beneficial. Some of these issues are summarised as follows:

- under -utilisation of plant machines
- too few machines in use to permit adequate experience
- operators continuing to place too much reliance on their own senses
- highly mobile equipment

It is not surprising, therefore to find it difficult to make the decision whether to use condition monitoring, and if so, which techniques to use. An early programme designed to assist industry in grappling with these issues was initiated in the U.K. by the Department of Trade and Industry. M.J.Neale and Associates were commissioned to conduct a survey which was published in 1979 [1]. In 1986, Rao [2] published details of a model which was designed to enable better use of failure and repair cost data. A method for justifying the use of condition monitoring methods in maintenance is in use by the Management Consultants, Moret Ernst and Young in the Netherlands, [3], in which the cost of using condition monitoring is compared against the cost of the alternative technologies, such as Time-Based Maintenance(TBM), or eliminating the consequential cost of a breakdown, etc. However, the model adopted for this study is based on that developed originally by Rajan [4]. This approach was adopted because it is based on a group of similar machines and hence, increases the probability of obtaining real cost savings, thus making it easier to justify the cost of employing condition monitoring methods.

This development was undertaken in the first instance to deal with batch process situations of the type experienced in the pharmaceutical products industry. The first step was to develop the model for pumps with standby facilities, in which it can be reasonably assumed that there will be no consequential costs due to failure.
Subsequently, the model was refined to take account of consequential costs and then was applied to examine instances where there were no standby facilities, such fans,[5] and also, gearbox installations [6].
The purpose of this investigation, therefore, was to establish whether the same model, or some variant of it, can be utilised for assessing the cost benefits of using condition monitoring in an entirely different industry, such as, e.g., the steel industry. This paper, therefore sets out to describe the way in which the original model was first adapted and then used to obtain some initial results of analysis for a hydraulics system situated in the hot rolling mill.
Development of the revised model: The essence of the model is a comparison of possible maintenance budget savings by comparing breakdown maintenance with the running costs of condition-based maintenance. The savings possible take into account both the direct and consequential costs of failure and the model is presented in the form of simple equations in conjunction with a MS Excel spreadsheet. The equations used for the cost comparisons differ for each group of machines under consideration but the basis of the comparison remain the same. Commencing with Rajan's cost model developed for pumps in which only the direct costs were involved, the predicted pump condition monitoring savings are:

$$Cs = 0.8\,[D]^*\,[\textit{unreliability}]^*[Rc] - [\text{CBM cost}] \qquad (1)$$

Where: Rc = direct costs of failure
CBM = condition-based maintenance
and reliability is determined by consideration of the Mean Time Between Failure in a Poisson-based failure distribution
The factor 0.8 is a factor to allow for the money that can be saved through the application of CBM instead of Breakdown Maintenance (BDM).
In addition, because no condition monitoring programme is capable of detecting all failures, a factor, 0.75, is introduced to represent the savings possible from using either high or low level monitoring systems - denoted as D, which is determined using the procedure outlined in reference 4.
The predicted repair cost is represented by the equation:

$$Rc = Cc^*Ip^*Ic^*Ipr^*Kd \qquad (2)$$

where: Cc = capital cost of machinery
Ip = power index
Ic = criticality index
Ipr = process index
Kd = direct cost factor

For further details of the development of equation 2, see reference 4. However, examination of the hot strip mill operating condition revealed that the equation required to be changed, leading to:

$$Rc = Cc^*Ip^*Ic^*Kd \qquad (3)$$

Equation 1 also includes the running costs of monitoring the condition of the pumps, and they can be sub-divided into variable and constant costs. The former are the hours required for measurement and analysis of the condition monitoring data (T), multiplied by the hourly labour costs, (L). The latter costs are those which account for the capital cost of the monitoring equipment, (VI) divided by the amortisation period and taking into account the number of items(pumps, say) - (N). The amortisation period represents, therefore, the total number of years the equipment can be effectively utilised before it is totally incapable of further use.
Hence, we have:

$$C = T*L + \left\{\frac{VI}{amortisation*N}\right\} \qquad (4)$$

The decision whether to utilise condition monitoring is made by reference to the costs of performing condition monitoring when compared with the predicted savings based on the criterion: $N*[\textit{pay-back period}] > \frac{VI}{Cs}$

For situations in which there is no standby facility, Rajan's equation 1 now becomes:

$$Cs = 0.8*[D]*[\textit{unreliability}]*[Rc] + [D]*[\textit{unreliability}]Rq - [\text{CBM cost}] \qquad (5)$$

Where: Rq = consequential costs of failure = Ip*Ipr*Ic*Kc
Kc = consequential cost factor

Utilising the above equations leads to the determination of the number of machines required in a given group to make CBM viable. This approach is based on the expectation that similar savings can be achieved within a group of identical machines, and that 'small' savings can add up sufficiently to justify the use of CBM on a 'self-fundable' basis.
In the case of a hot rolling mill of an integrated steelworks, it requires that a group of identical or similar machine types be identified that are, nevertheless, critical as regards to their effect on the efficiency and availability of the mill operation if they should fail with consequential mill down-time implications.
A representative example of such a group is the deployment of hydraulic pumps. Some of these locations have multiple pump installations operating with a single standby pump. Based on Rajan's results [4], the equation for Kd is given by:

$$Kd = (74.58.\ 10^{-4})*\ e^{(-0.009*POWER)} \qquad (6)$$

For the hot strip mill, the possibility of consequential costs has to be allowed for in which the costs of a failure are counted in terms of downtime and product loss. The costs incurred through downtime on the mill can vary by an order of magnitude from as little as $1500 per minute. The consequential costs of the loss of product may be assumed to have an average constant value. The other consequential cost implication relates to the effect of standby facility failure, and hence, the probability of detection of machine deterioration, D is taken into consideration. This is combined with the consequential cost probability on the assumption that a stand-by pump does not fail before being activated, and hence condition monitored.

Therefore, based on this premise:

$$\text{System Failure Cost} = (D^* [1-R(t)]^{(standby+1)})^* \{\textit{downtime}^* X + Y\} \quad (7)$$

where: $R(t)$ = Reliability

X = Downtime cost per minute

Y = Product value

and hence, $Rq = \dfrac{\text{System Failure Cost}}{\text{Standby} + 1}$

Further rationalisation and refinement of the above requirements through analysis of the mill operationg condition, leads to the final set of equations as follows:

$$Cs = 0.8^*D^*[1-R(t)]^*Rc + Rq - \text{CBM costs} \quad (8)$$

$$Rc = Cc^*Ip^*Ic^*Kd \quad (9)$$

$$Rq = \frac{(D^*[1-R(t)]^{(standby+1)} * \{(\text{Down-time} * X) + Y\}}{\text{standby} + 1} \quad (10)$$

$$\text{CBM cost} = L^*T + \frac{VI^*(bi)^{pb} * T}{pb^*TT^*U} \quad (11)$$

where: bi = base rate of interest

pb = pay-back period (years)

TT = total time available for equipment utilisation

U = degree of equipment utilisation (%)

Note: These equations are only applicable for the hydraulic pump systems and are expressed in terms of the savings per machine.

Results: The revised model was used to analyse several hydraulic pump systems operating in the hot rolling mill and which were selected initially on the basis that the information required was available. Even so, using this approach still posed a number of problems in obtaining all the information required. For this reason, a sensitivity test was instituted so that the effect of any variations or uncertainties in applying the data could be tested and evaluated. The results presented here are representative of a considerable amount of analysis undertaken to establish the effects of these variables on the cost prediction capability of the model.

Among the variables that may influence the decisions to be taken, the following were considered to be of particular relevance and interest:

- Possible savings ratio between BDM and CBM repair cost
- Probability of machinery deterioration detection
- Reliability of machinery
- Average system downtime
- Time available for condition monitoring equipment usage

Varying the savings ratio from the notional value of 0.8 (the same value used by Rajan, [4]) up to 1.25 shows that for an increase of 56%, there is only an increase in savings here of just over 2%. This is a direct result of the high consequential costs of system failure. The probability of detection 'norm' achieved by using condition monitoring

is 0.75. A variation in this value from 0.6 to 0.85 reveals that it has significant influence on the outcome, as demonstrated by Figure 1, in which there is a fluctuation in savings of -39% to +31% within this range. If the range is expanded from 0.1 to 0.95 confirms that it is a highly non-linear characteristic. A detection in machinery deterioration above 50% appears to signal when condition monitoring really begins to take effect.

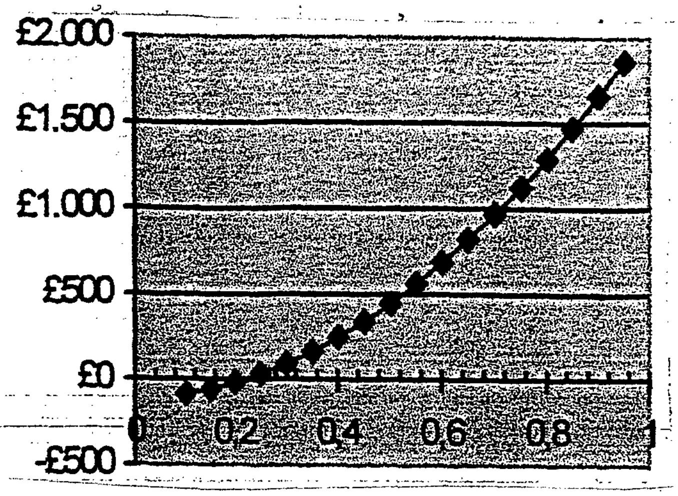

Figure 1 Variation in deterioration factor

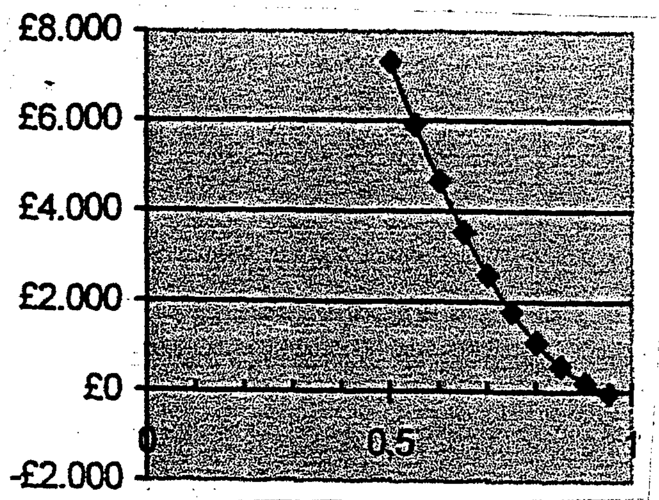

Figure 2 Variation in reliability

Past results have shown that the reliability of hydraulic pumps is approximately 80% for the hot strip mill. Figure 2 shows that by varying the reliability from 50 to 95 %, has considerable impact on the savings possible in which it becomes much harder to justify the cost of condition monitoring as the reliability improves above about 75%. This demonstrates the importance of achieving a correct definition of failure.
The impact of machine downtime costs is of particular interest, as shown by the results of a sensitivity test plotted in Figure 3, in which the range of interest: from as little as 1,500 to as much as 15,000 US dollars per minute reveals a linear response. [Note that the vertical axis of Figure 3 is scaled in pounds Sterling]. When the downtime cost falls below about $3,000 per minute, the case for using condition monitoring begins to become harder to justify. A clear identification of the downtime costs per minute is, therefore, essential. For the case where the downtime cost is $15,000 per minute, the results of a comparison between the variables under consideration and the condition monitoring savings per machine is summarised in Table 1 below. More detailed information is to be found in reference 7.

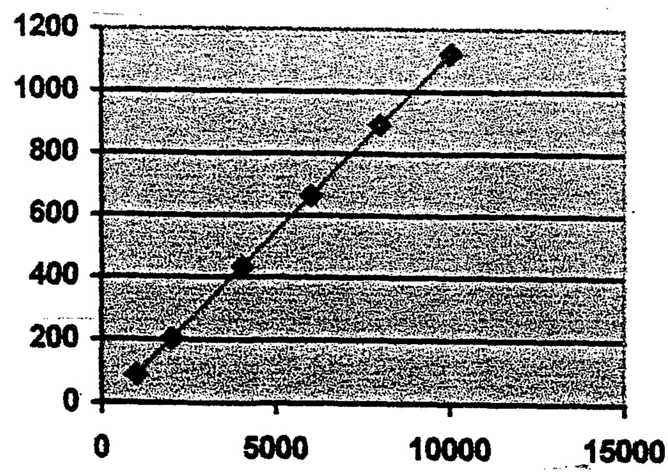

Figure 3 Influence of downtime cost

Table 1 The effect of process variables on cost savings

VARIABLE	SAVINGS PER MACHINE		
		Sensitivity	
	Hardly	Very	Extremely
Savings factor between CBM and BDM	√		
Probability of deterioration detection		√	
Machine reliability		√	
Repair cost prediction inaccuracy	√		
Machine type assessed (cost + power)	√		
Stand-by facilities			√
Equipment purchase cost	√		
Pay-back period	√		
Labour cost per hour	√		
Time required per year for con. mon.	√		
Degree of equipment utilisation			√

Conclusions: Certain parameters influence the justification of condition-based maintenance more than others. For the case of the hydraulic pumps sited on the hot rolling mill of an integrated steelworks, the operations are very sensitive to:

- Probability of deterioration detection
- Machine reliability
- Number of stand-by facilities
- Degree of condition monitoring equipment utilisation
- System failure downtime duration

The model can be utilised in the first instance as a means of convincing company management the extent to which condition-based maintenance can be employed with a reasonable expectation of achieving realistic savings.

Ultimately, the most important utilisation of the model will be its use in conjunction with the prediction of remaining useful life of equipment and hence, strategically where best to deploy condition monitoring facilities and manpower.

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